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A METHOD OF INCREMENTAL RECORDING ON MAGNETIC TAPE

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ACKNOWLEDGMENT

A number of ideas described in this report were conceived during 1955, at the time that Mr. M.I. Lipanovich* was head of the Laboratory Instrumentation Program of the Instruments Branch, USNRDL. The authors wish to express their gratitude to Mr. Lipanovich for the many contributions which he made to this work.

*NOTE: M.I. Lipanovich is now employed by Lockheed Missile and Space Division, Lockheed Aircraft Corporation, Palo Alto, Calif.

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ABSTRACT

The conventional method of recording pulse data on magnetic tape fails to fully utilize the optimum bit-packing capability of the recording tape at pulse rates less than the design maximum. A simple method of incremental recording is described wherein the tape is stepped one increment of length for each serial input pulse, allowing optimum bit packing which is independent of pulse rate. The method is applicable to multi-channel recording of variable pulse rates up to 100 pps and to recording mediums other than magnetic tape. It is advantageous where low power drain and long recording time without tape reloading are required. An experimental miniature incremental magnetic tape recorder, utilizing a commercially available stepping motor and having transistorized logic and drive circuitry is described. Test results are given and a method of data analysis for incrementally recorded tape by means of conventional playback is presented.

SUMMARY

The Problem

Design and fabricate an experimental incremental recorder and determine the step length precision.

The Findings

A miniature incremental recorder, using a standard stepping motor for tape movement and requiring minimum operating power, has been designed, fabricated, and tested. Additional refinement of mechanical design and circuitry is required to reduce step length variability which was found to be as high as 12 percent. The method has application to recording problems requiring long recording periods of variable pulse rate up to 100 pps.

INTRODUCTION

In the conventional method of magnetic tape data recording, the tape is moved past the recording head at a fixed speed independent of the input data rate. Optimum recorded bit density is achieved, during direct pulse recording, only at the highest pulse repetition rate for which the recorder was designed. The optimum bit density which can be achieved in a given application is determined by the design of the recording and reproducing heads, the characteristics of the magnetic tape, and the precision of the tape motion.[1] Whenever the input pulse repetition rate becomes less than the design maximum, the recorded bit density becomes less than optimum, resulting in what may be termed "storage loss," since the tape speed is independent of the pulse rate being recorded. Storage loss can be reduced by making the tape movement dependent upon the input pulse rate and may be accomplished by moving the tape one discrete increment of length for each serial input pulse. This method may be termed "incremental" recording.

The incremental method of recording is employed in many digital magnetic recorders now in use. In these recorders the tape is moved in discrete lengths at a synchronous rate on data command, usually by the start-stop action resulting when a pressure roller is momentarily moved against the tape, in contact with a constantly rotating capstan. For computer applications, the high speed and precision of tape motion which must be achieved necessitate complex mechanical and electrical systems. These systems are ac operated and generally large and costly.

However, in some applications of recording serial pulse data, high precision is not a requirement, whereas conservation of power, portability, and cost are important factors. In this report a new method of incremental recording which meets these requirements and a technique for playback are described. The recording method reported utilizes a standard stepping motor to move the tape one discrete increment of length for each serial input pulse of data or time. It is suitable for low cost, battery-operated portable recorders in applications which do

not demand high time resolution or which allow time resolution to be compromised for increased storage on the tape.

APPROACH

Recording Method

Figure 1 shows basic circuitry required for the incremental recorder. A three-channel system is shown, although additional channels might be similarly used.

As each input pulse arrives on any channel, it is recorded on the tape and, by means of the amplifying circuitry and stepping motor, it causes the tape to be advanced one increment. For incremental recording, the length of each step of the tape is fixed by the angular displacement of the stepping motor, the gear reduction, and the capstan diameter. This length is optimized to the minimum space required on the tape for the recording of one bit.[1]

A graphic illustration of a three-channel incrementally recorded tape is shown in Figure 2. In this illustration, channels 1 and 2 are data channels designated d and d'; channel 3 is a timing channel designated as t. The nominal step width illustrated is .005 in.

In channels 1 and 2, the data are represented by the number of data bits (d and d') recorded in each channel as a function of time. In channel 3, all timing bits (t) represent 1-sec increments of time regardless of spacing; i.e., time t_1 to t_2 is 1 sec; time t_2 to t_{19} is 17 sec.

In channel 1, less than 100 bits are represented between t_1 and t_2. The repetition rate is increasing and reaches a rate of 100 pps at d_{100}. Beyond this point, the design maximum, further recording and tape drive by channel 2 is blocked by logic circuitry which will be discussed.

For the system illustrated, channels 1 and 2 record simultaneously and have input pulse repetition rates in the ratio of 1000:1. Therefore, channel 1 is represented with a bit spacing, or time period, of about 0.01 sec, and the spacing in channel 2 between d'_1 and d'_2 is shown as approximately 10 sec. Also in channel 2, the spacing between d'_2 and d'_3 is shown as 9 sec to illustrate an increasing rate in that channel.

Since bits are recorded serially with time, the channel having the highest input pulse rate has the highest recorded bit density and also is the predominant driving channel. In Figure 2, channel 1 is predominant until it is blocked from recording and driving at bit d_{100}. At this point channel 3, which has the highest input pulse rate, is the predominant driving channel.

Recorded bits in the predominant driving channel are evenly spaced at the nominal step length except when a noncoincident data pulse occurs in another channel. Such a pulse causes a gap of one step length in the bit spacing of the predominant channel. This situation is illustrated in Figure 2 by the gap between pulses d_1 and d_2 in channel 1 caused by the noncoincident pulse d_1' in channel 2. Coincidence between input pulses in two or more channels causes but one step of the tape and therefore does not cause a gap in the bit spacing of the predominant channel. Pulse coincidence is illustrated between bits d_2 and t_1, d_{100} and t_2, d_2' and t_{10}, and d_3' and t_{19}. It should be noted that noncoincident pulses which occur during a drive cycle will cause but one step of the tape. Therefore, the possibility exists that occasionally bits will be recorded over previously recorded bits when a noncoincident pulse occurs during the end of a drive cycle and is followed by a driving pulse in that same channel.

If optimum recorded bit spacing is 0.005 in., then storage loss is greatly reduced if at least one bit is recorded in any one channel for each segment of 0.005 in. over the tape length. Since the basis of the incremental method is one tape step for each recorded noncoincident input pulse, this condition is achieved, as Figure 2 illustrates.

Playback Method

The rate of the incrementally recorded data is computed during playback on a conventional playback recorder at any convenient tape speed. Since the time bits recorded in the timing channel represent true time, this channel may serve as a time base against which the data channels may be compared. This comparison can be made by counting the number of recorded data bits in a data channel spaced between recorded time bits in the timing channel. Standard pulse counting equipment may be used for this purpose as illustrated in the block diagram of Figure 3.

With this playback method for an incrementally recorded tape, the final data has the same form as that obtained from a conventionally recorded tape by the same playback method, within the time resolution capabilities of the incremental system.

Storage Capability

The storage capability of an incremental recorder and a conventional recorder may be compared directly, provided each recorder has identical tape capacity, recording head gap length, and recording pulse rate capability.

A conventional recorder having a tape speed of 0.25 in./sec and a recording head gap length of 0.0004 in. has, conservatively, a capability to record a range of pulse rates from 0 to 100 pps.[1,2] With a tape capacity of 900 ft this recorder will record continuously without tape reloading for a period of 12 hr.

An incremental recorder having the same recording head gap length, the same tape capacity, and designed for an incremental tape step of 0.005 in./pulse, has a tape speed range which varies from 0 to 0.5 in./sec over the pulse rate range of 0 to 100 pps.

It should be noted that the parameters established for this comparison yield a packing density of 400 bits per inch of tape at the maximum rate of 100 pps for the conventional recorder. For the incremental recorder the same maximum rate yields a packing density of 200 bits per inch, due to the length of the step selected. Since the tape speed of the incremental recorder varies according to the input pulse rate, a tabulation of rate versus recording time is of interest. Such a tabulation is presented in Table 1. If the maximum packing density of 400 bits per inch were achieved, the recording time would be essentially two times the values shown in this table.

Since the conventional recorder described has a fixed recording time of 12 hr, it is evident from Table 1 that for pulse repetition rates of less than about 50 pps, the incremental recorder has the higher storage capability. This comparison shows that the incremental recording method is particularly applicable to long term recording where it is predictable that the average input rate will be below 50 pps. Where it is predictable that the average rate will exceed 50 pps the conventional recording method is advantageous for the conditions described.

TABLE 1

Minimum Recording Time vs. Input Pulse Rate for One Data Channel of the Incremental Recorder

Data Pulse Rate (Pulses/sec)	Minimum Hours of Recording Time*
0	600
1	300
10	54.5
20	28.6
30	19.4
40	14.6
50	11.8
60	9.84
70	8.45
80	7.41
90	6.59
100	5.94

*For tape length of 900 ft, step length of 0.005 in., and timing pulse rate of 1 pulse/sec.

DESCRIPTION

Incremental Recorder

A conventional miniature type of recorder* was converted into an incremental type of recorder to implement an evaluation study of this incremental recording method. The unmodified recorder had a rated tape speed of 0.25 in./sec and utilized 900 ft of 1/4-in. wide, 1-mil thick, Mylar recording tape on standard 5-in. diameter tape reels which provided a recording time of 12 hr. A three-channel in-line type head**, having a head gap length of 0.0004 in., was used. This recorder was selected for the conversion primarily because of its low tape drive torque requirement. Figures 4a and 4b are photographs of the recorder as modifed for incremental recording.

To convert the recorder to incremental drive, the capstan drive motor was replaced by a "Cyclonome Stepping Motor," series 9AB01***. No modification of the speed reduction train or the capstan diameter was made.

The stepping motor rotates 18 deg for each phase reversal of the driving signal. When the driving signal is not sinusoidal, the circuitry must provide drive energy which is effectively AC. For 18 deg steps, the motor is rated at 260 steps per second. In this application, the simplified circuitry used provided 2 phase reversals for each input pulse, causing the motor to rotate 36 deg per step or 130 steps/second.

The stepping motor driving the 0.24-in. diameter capstan of the recorder through its 15/1 speed reducing system resulted in the nominal tape step length of 0.005 in. per input pulse.

Motor Characteristics

The motor is available with winding resistances from 1.2 to 3,400 ohms. For the application described, a winding having a resistance of 1.2 ohms was used to achieve an effective transfer of power from the final transistor stage of the motor drive circuit.

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*The Model T-112, manufactured by Precision Instrument Co., San Carlos, Calif.

**Brush Type BK-1303.

***Manufactured by Sigma Instruments, Inc., So. Braintree, Mass.

The drive torque requirement of the conventional recorder as modified for incremental recording was measured to be 35 g-cm. The stepping motor used had a maximum rated torque of 80 g-cm and required 1/3 to 40 w input power, depending upon speed and mechanical loading.

The motor manufacturer has available several types of shaft couplers and dampers designed to match the motor to the inertia and friction of a specific load. The type AT10 pneumatic damper was used as both damper and coupler in this application.

PERFORMANCE

Test Procedures

The incremental recorder described was tested to determine the general quality of performance and precision of tape step length. The tests included one-channel and two-channel recordings. No three-channel recording tests were made.

For these tests the circuit shown in Figure 1 was used. A negative input pulse of about 3.5 v amplitude and about 5.0-ms width was used as a motor drive pulse for all one-channel tests. Where two-channel tests were performed, two such signals from separate pulse sources were used. A minimum length of 6 ft of tape was recorded during each test run.

One-channel recordings were made to determine the deviation of the step length of the recorder from the design value as a function of input pulse rate. In one series of tests, the 5.0-ms motor drive pulse was also used for recording. Under this condition, recording occurred during tape motion. However, it was found that the tape motion was delayed by about 1 ms due to system inertia; and in a second series of tests, a 0.3-ms recording pulse, synchronized with the start of the drive, was used to assure recording of the pulse before the tape motion started, thereby improving the resolution of the recorded bits.

At a constant playback speed of 7 1/2 in./sec, it was expected that the period of pulses recorded at a step length of .005 in. would be

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*Manufactured by Sigma Instruments, Inc., So. Braintree, Mass.

0.67 ms and would be independent of the period of the recorded pulse. The deviation of the step length was determined during playback by comparing the measured period to the expected period of 0.67 ms.

Two-channel recordings were made to establish the feasibility of this method of recording multichannel pulse data as a function of time. In these tests, either a 1- or 10-pps timing pulse was recorded in the timing channel, and data pulses of equal or higher repetition rate were recorded in a second channel. The ratio of the pulse rates recorded on the two channels was made constant. During playback, the ratio was measured as illustrated in Figure 3. Performance was determined by comparing these ratios.

Test Results

Step Length Deviation. Table 2 summarizes the results of the one-channel recording tests. The uncertainty in these tests was estimated to be less than ±1 percent.

TABLE 2

Summary of Results of One-Channel Tests Showing Step Length Deviation

	Rep. Rate (pps)	Percent Deviation* For 5.0 ms Record Pulse			Percent Deviation* For 0.3 ms Record Pulse		
		High	Average	Low	High	Average	Low
(a)	60	+3.0	-1.1	-4.6			
(b)	60	+0.7	-0.2	-1.2			
(c)	100	+10.0	0	-9.1	+6.1	-0.4	-12.1
(d)	100	+0.5	-0.6	-2.0	+0.8	-0.2	-1.8

$$\text{*Percent deviation} = \frac{\text{Measured Period} - \text{Expected Period}}{\text{Expected Period}} \times 100\%$$

NOTE: Step length deviation is proportional to the period deviation. The average deviation for (a) and (c) was based upon approximately 100 period measurements. The average deviation for (b) and (d) was based upon approximately 10 measurements of the average of ten periods.

Although data are shown for recorded repetition rates of 60 and 100 pps, the tests included repetition rates as low as 1 pps. Performance below 60 pps did not differ significantly from that shown in Table 2 for 60 pps. The increase in the deviation of the step length from that of the 60 pps test to that of the 100 pps test is attributed to inefficient drive circuitry combined with mechanical resonances in the capstan drive linkage. Performance will be considerably improved by use of more elaborate circuitry and by selecting a more suitable coupling to the stepping motor. Further evidence of unsatisfactory motor coupling was found during tests as the input pulse rate was slowly varied over a range of 1 to 100 pps. Occasionally, the direction of shaft rotation would reverse, indicating excessive load inertia and the need for additional compliance in the coupling.

The step length deviation, shown in (a) and (d) of Table 2, established the maximum tolerance of the length of tape moved in a single step. This tolerance was a maximum of about 12 percent at 100 pps, the pulse rate design limit of the recorder. Therefore, the step length achieved was a minimum of about .0044 in. and a maximum of .0056 in. of tape length, well over the minimum of .0025 in. required for satisfactory bit resolution with the recording head and tape used. Consequently, a step length shorter than 0.005 in. could have been used.

<u>Two-Channel Recording</u>. Table 3 summarizes the results of the two-channel recording tests.

TABLE 3

Summary of Results of Two-Channel Tests

Recorded Rep. Rate Data Chan (pps)	Recorded Rep. Rate Time Chan (pps)	Recorded Ratio	Playback Ratio High	Playback Ratio Low	% Deviation* High	% Deviation* Low	% Deviation** Expected
10	10	1	1.00	1.00	0	0	±100
10	1	10	10.0	9.00	0	-10.0	±10
50	1	50	51.0	47.0	+2.00	-6.00	±2
50	10	5	5.00	4.00	0	-20.0	±20
66	1	66	68.0	55.0	+3.00	-16.7	±1.52

$$\text{*Percent deviation} = \frac{\text{Playback ratio} - \text{Recorded Ratio}}{\text{Recorded Ratio}} \times 100\%$$

**Due to system resolution = ±1 increment

These results demonstrate that above 50 pps the deviation measured generally exceeded the maximum deviation which would be expected from the system resolution alone. (The system cannot resolve fractions of an increment.) From these data and visual observation during recording, it was determined that the excess deviation resulted from the inability of the recorder to reliably resolve pulses from either channel which arrived within a time of about 10 ms. The presence of drive pulses separated by less than 10 ms tended to disrupt the normal stepping cycle of the motor and resulted in a loss or increase of steps.

This condition may be eliminated by the system shown in Figure 5. In this circuit, an "And" gate is inserted before the power amplifier and a univibrator (SS4) is placed in a feedback loop from the power amplifier output to the control input of the "And" gate. The "And" gate passes data pulses when no signal is present at its control input. The first data pulse through the gate passes to the power amplifier as a 5-ms pulse, driving the stepping motor. The trailing edge of this pulse is used to trigger the univibrator, producing a 5-ms "off" pulse at the control input of the "And" gate. The gate therefore rejects all pulses occurring within 5 ms of the end of a driving signal and ensures a minimum spacing of 10 ms between driving pulses. However, all pulses are recorded in the two channels of the magnetic tape, as previously described.

Resolution. The pulse resolution and band width of the recorder were basically limited by the capability of the stepping motor to respond to two or more successive pulses. Pulse resolution as a function of input rate was checked by the technique of double pulsing. A 5-ms drive pulse was introduced to one input of the recorder (Fig. 1) and the same pulse, delayed by 10 ms, was introduced to the second input, thus ensuring drive from pulse pairs. Successive pulse pairs were generated up to a rate of 50/sec, the rate at which all pulses generated were separated by 10 ms and the effective drive was 100 pps. When driven in this manner, the response of the stepping motor, as observed visually, was satisfactory with pulse pairs in the range of 1 to 50/sec. The maximum resolution of the motor was not determined because of limitations imposed by the motor drive circuitry, which set the drive cycle at 10 ms.

Stepping Speed. Although the motor used is capable of 130 (36 deg) steps/sec, the design maximum synchronous input rate of the recorder was arbitrarily limited to 100 pps. Where it is predictable that the input pulse rate of a channel may exceed the maximum stepping rate of the recorder, provision must be made for motor drive cut-off beyond that rate. No such provision was made in the design of this recorder. A circuit to perform this function is shown in Figure 5, and includes

the circuitry inserted between the two "pulse shapers" in "channel 1."

In operation, the control gate is normally on and an input pulse passes to the pulse shaper. Each input pulse triggers univibrator SS1 which triggers univibrator SS2 after a 1-ms delay. The output of SS2 closes the control gate for 9 ms and is also applied to the "And" gate. A second input pulse, and all subsequent pulses, spaced by 10 ms or more, pass through the control gate which is returned to the "on" condition within the 10-ms time interval. However, a second pulse spaced by less than 10 ms from the initial pulse will be blocked by the control gate which is held "off" by SS2. Also, univibrator SS3 is triggered by the input pulse through the "And" gate and its output is applied to the gate for 11 ms, keeping the control gate "off" after SS2 returns to its normal state. The pulse width of SS3 was selected arbitrarily to provide a high probability of overlap between the outputs of SS2 and SS3 for pulse rates above 100 pps. Therefore, essentially all subsequent pulses spaced by less than 10 ms continue to be blocked by the control gate which is held "off" by the output of SS2 or SS3. (Other circuits may be utilized to perform this function.)

Shielding. The proximity of the recording head to the stepping motor necessitated magnetic shielding. It was found that three sheets of .005-in. thick Netic S-3-6* material between the motor and recording head reduced the magnetic field at the head to a satisfactory level.

CONCLUSIONS AND RECOMMENDATIONS

In the recording of pulse data of variable rate, the incremental recording method is applicable as a means of conserving tape footage and increasing recording time capability. This statement implies reduced playback time for a given recorded data span. Basically, the method is suitable for all applications requiring constant bit density recording of digital data.

The method is attractive for many recording applications where battery operation is a requirement. The motor drive and logics circuitry may be transistorized by using standard components and techniques. Circuitry may be designed to be essentially cut off during periods between

*Manufactured by the Magnetic Shield Division of the Perfection Mica Co., Chicago, Ill.

input pulses, thereby conserving power.

Within the present techniques, incremental magnetic recording is limited by the capability of the stepping motor to a relatively low range of pulse rates. For the recorder described, the maximum synchronous pulse rate is limited to about 125 pps.

The step length is limited primarily by the optimum bit density for the recording head and tape used and by the precision of the step motion. The optimum bit density of the recorder described was 400 bits/in., resulting in a minimum possible length of .0025 in. The precision of the step motion actually achieved would allow the nominal .005-in. step used to be reduced to .004 in. or less without reducing the reliability of the recorder. The reduced step length would allow an increase in recorded bit density of at least 25 percent, with a similar increase in recording time capability.

Promising areas for further investigation are outlined below:

1. Circuitry. The circuit refinements described should be developed.

2. Stepping Motors. A survey of available stepping motors is advisable. In particular, the Digitork Model S18* should be investigated. The manufacturer claims instantaneous starting at rates up to 600 cps for this motor, although 24 V/DC operation is a requirement.

3. Tape Drive Techniques. Since only a .005-in. tape step is required, reciprocating rather than rotating motions to drive the tape, such as may be applied by solenoid or magneto-strictive devices, are an interesting possibility.

4. Reduced Recording Head Gap Length. Use of a micro-gap recording head would allow an increase in recorded bit density and make possible a shorter incremental tape step.

5. Spring Power Drive. A promising means of reducing the drive power requirement is by use of a Negator spring**. The power of the Negator spring might be released through an escapement controlled by the input pulse rate.

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* Pace Controls Corporation, Needham Heights 94, Mass.

**Manufactured by the Hunter Spring Co., Lansdale, Pa.

6. <u>Other Incremental Techniques</u>. A variation in incremental recording of one channel of data is conceivable where the recorded time bit spacing is made proportional to the input data rate. Time bits are recorded; input data pulses step the tape but are not recorded. The data rate is determined during conventional playback as a function of the time period between recorded time bits. This technique essentially consolidates the time channel and one data channel. With this method, the time resolution is established by the recorded time base actuating the drive motor. By providing one or more time bases of a higher frequency on additional channels, the resolution of the recorder is increased proportionally. These time bases are recorded but do not actuate the stepping motor.

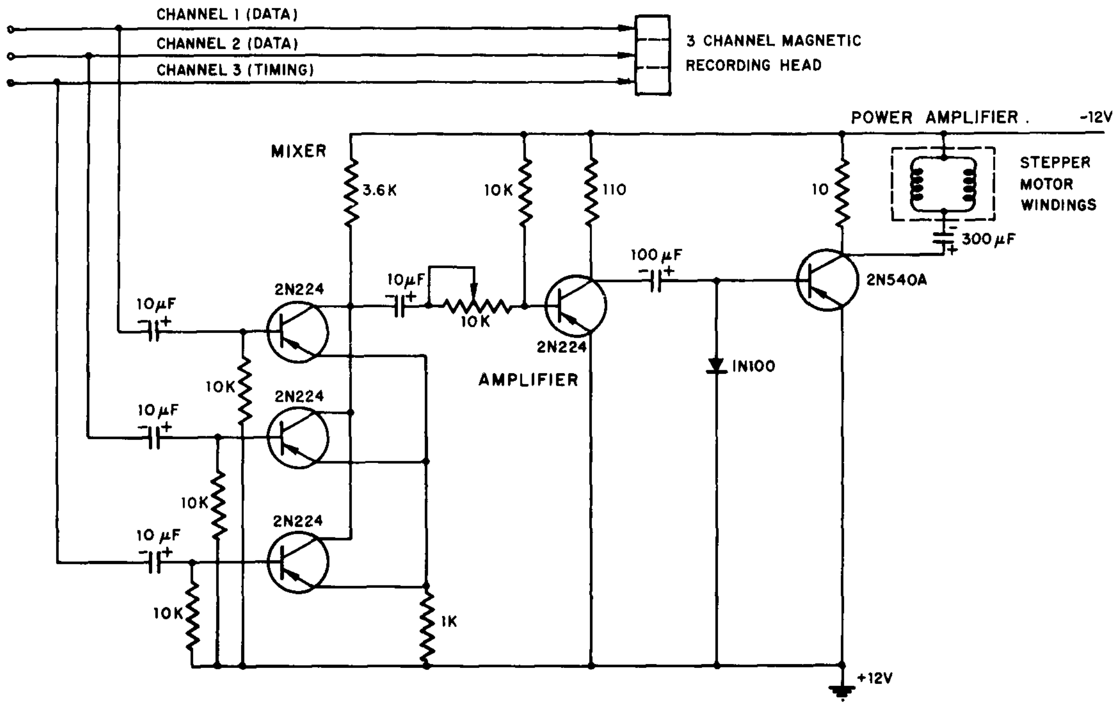

Fig. 1 Incremental Recorder Basic Drive Circuitry

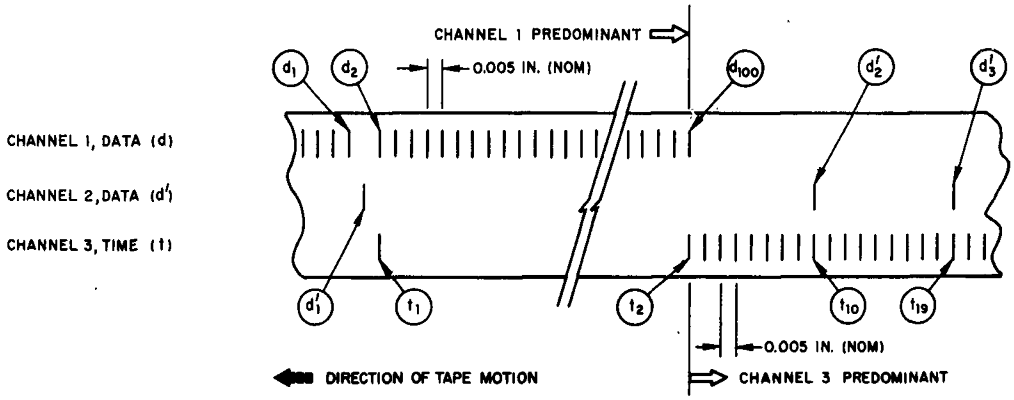

Fig. 2 Bit Alignment: Three-Channel Incrementally Recorded Tape

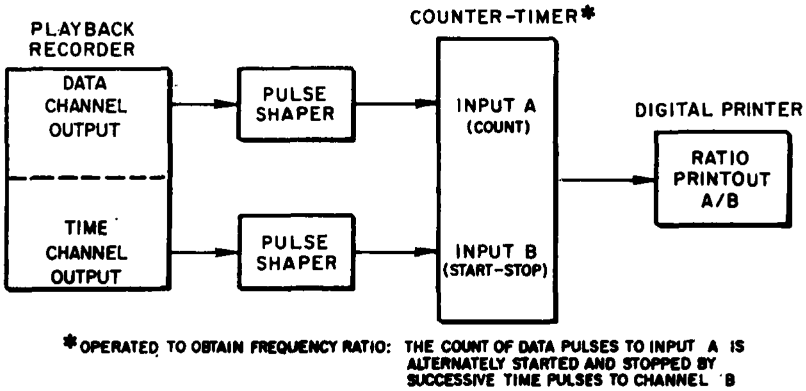

Fig. 3 Playback Equipment for Incrementally Recorded Tapes

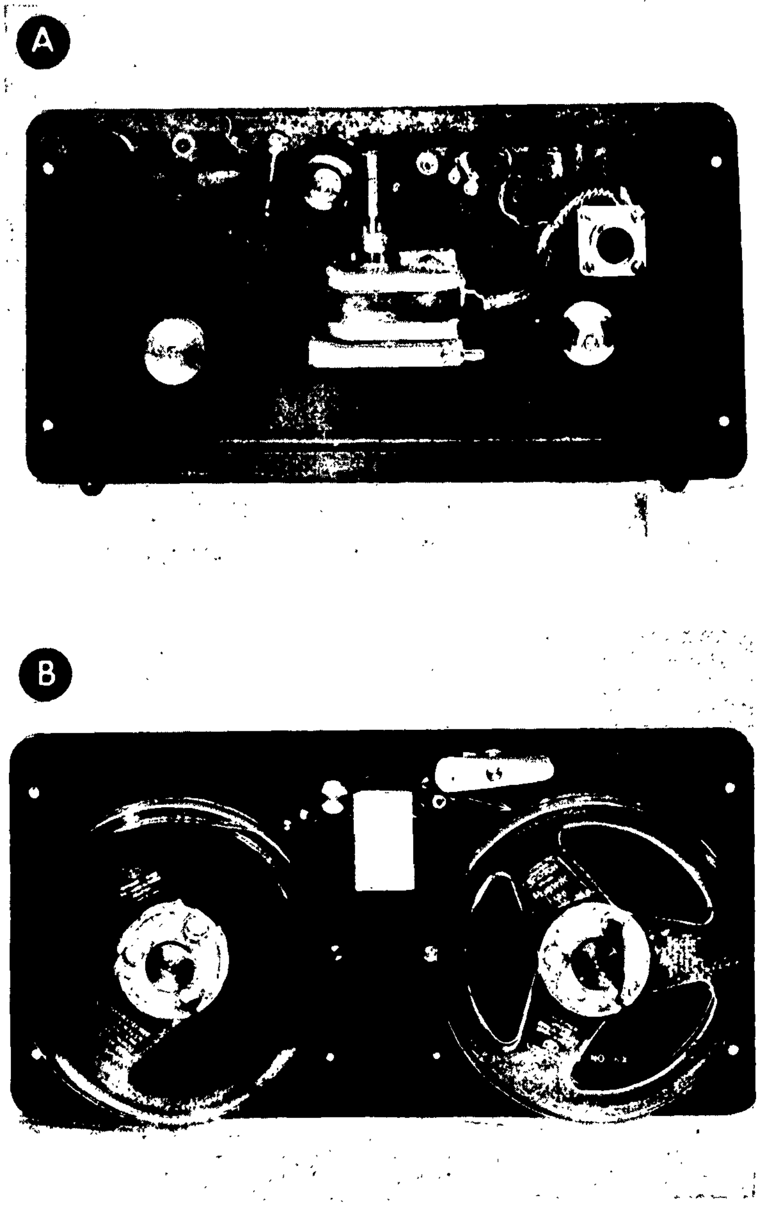

Fig. 4 Conventional Recorder Modified for Incremental Recording.
A. Modified drive, showing stepping motor replacing the conventional motor;
B. Unmodified front deck of the recorder.

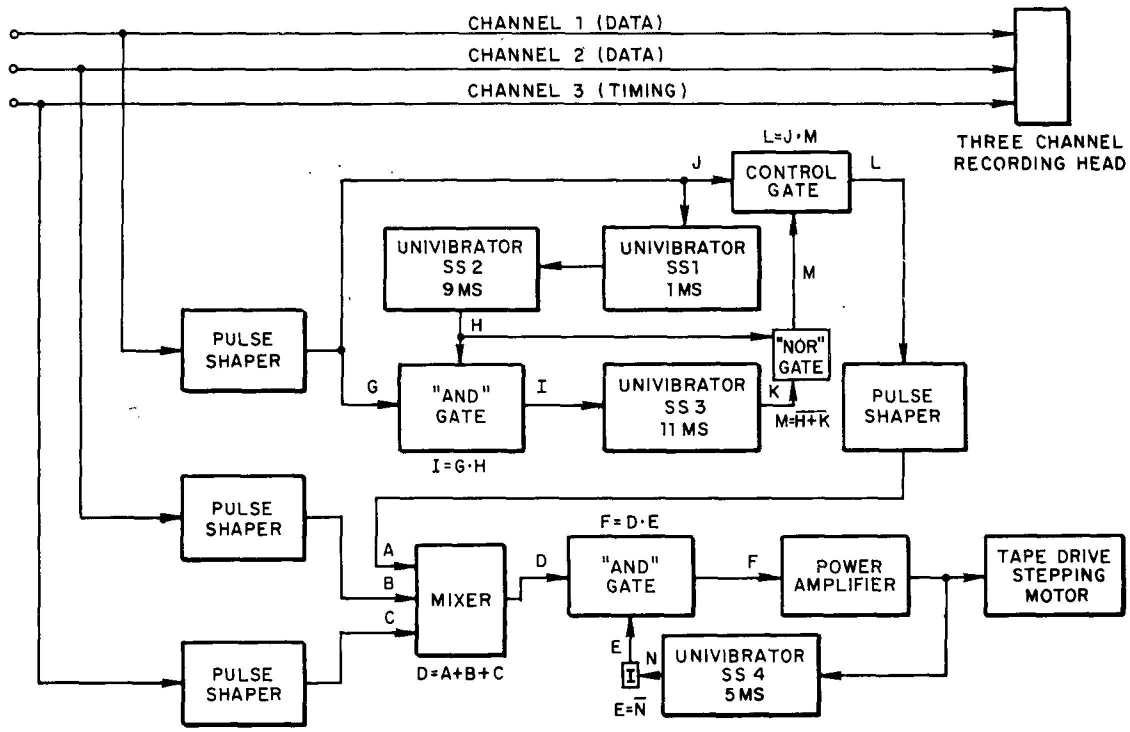

Fig. 5 Three-Channel Incremental Recording System

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